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Structured Light with Optical Fibres: Beams that Can Do What Gaussians Cannot

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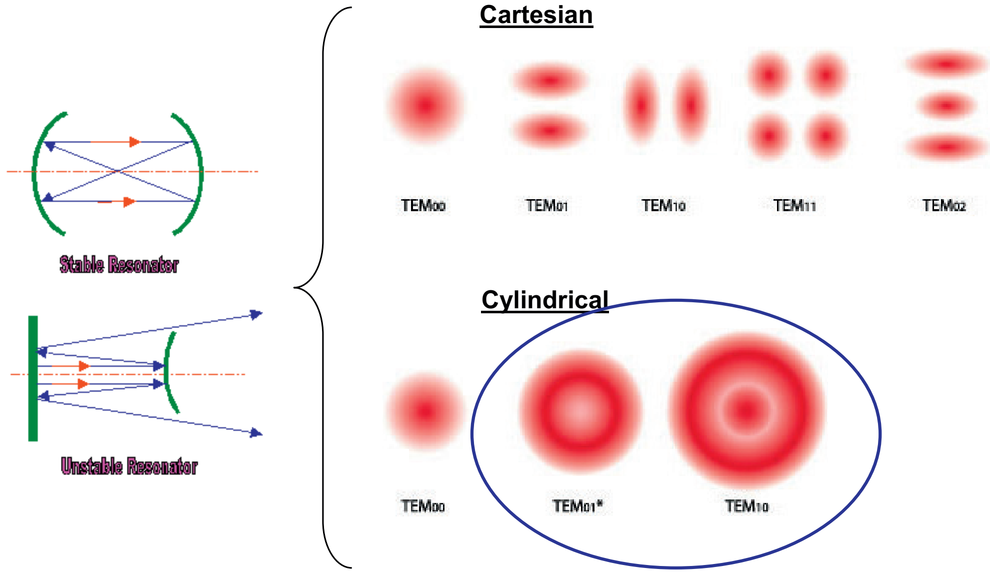
OFS & Bell Labs Colleagues, Collaborators at DoD, NIST, Cornell, Bath U., Max-Planck-Erlangen, Furukawa, UCI, Tel-Aviv U…several others.

Spatial modes



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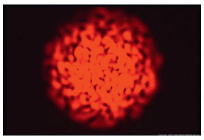
Mode Stability

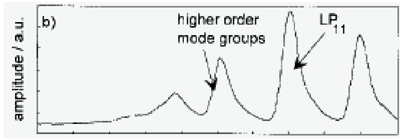
Multimode Fiber

Spatial Output

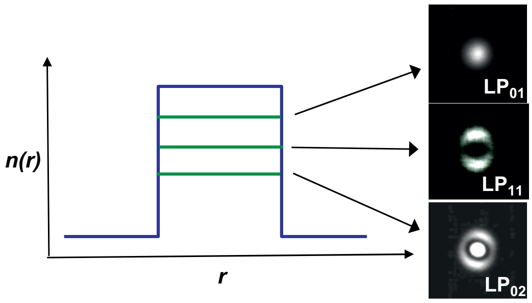


Vadim Makarov www.vad1.com

Temporal Output



Raddatz et al, PTL, v10, p534, 1998



$$\eta \sim \int E_1 \cdot P_{pert}(r,\varphi) \cdot E_2 \cdot dA$$

$$\delta(\lambda) = \frac{\Delta\beta(\lambda)}{2}$$

$$\delta \uparrow \Rightarrow coupling \downarrow$$

To exploit other modes…

- *Launch Purely*
- *Inhibit Coupling*

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Outline

- Mode Conversion
  - The higher-order-mode schematic
  - How to access them –*gratings, tapered couplers, holograms*
- Dispersion control
  - High normal (-ve) dispersion… *telecom, fs pulse control*
  - Anomalous Dispersion……….. *nonlinear optics*
  - Multiple paths…………………. *adjustable delays*
- Mode area control
  - Anomalous stability criteria ⇔ large mode areas
  - Applications to high-power lasers
- Free space implications
  - Beam forming
  - Cylindrical vector beams, Vortices
  - Bessel beams

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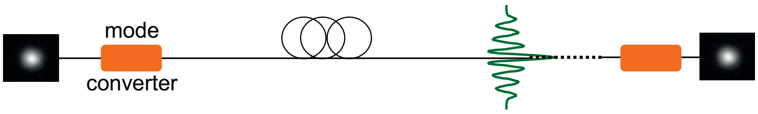
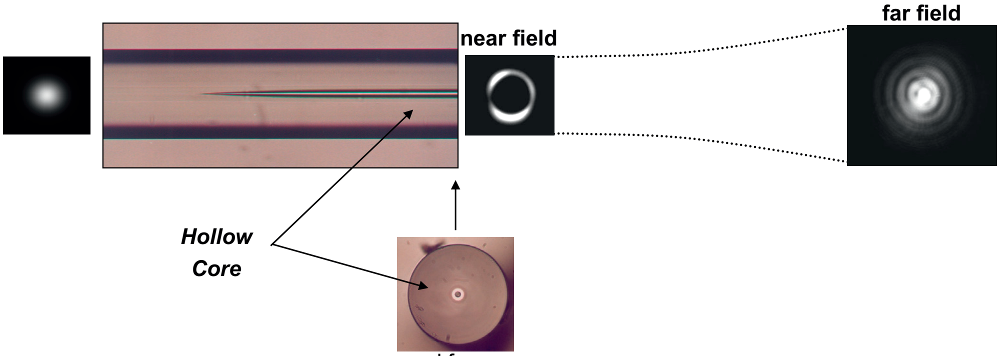
The HOM Schematic





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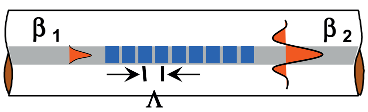
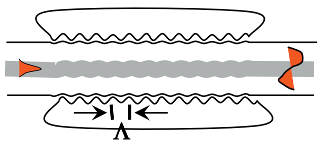
K. Oh et al, JLT, v23, p524, 2005

Long-period Fiber-gratings

UV-induced index change



Microbends



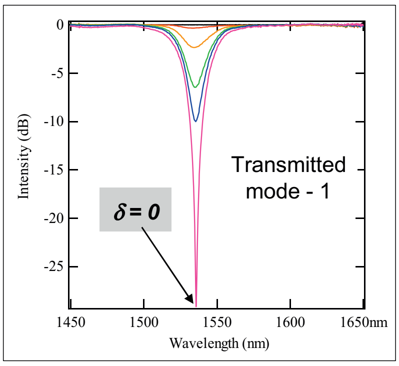
- Perturbation
  - break orthogonality between eigenmodes
  - symmetry of perturbation matters

$$\sim \int E_1 \cdot P_{pert}(r,\phi) \cdot E_2 \cdot dA$$

- Match phases
  - periodicity in real-space ⇔ singularity in k-space

$$\delta(\lambda) = \frac{\Delta\beta(\lambda)}{2} - \frac{\pi}{\Lambda}$$

  - maximum coupling for $\delta = 0$



J.N. Blake et al, OL, v11, p177, 1986
A.M. Vengsarkar, JLT, v14, p58, 1996

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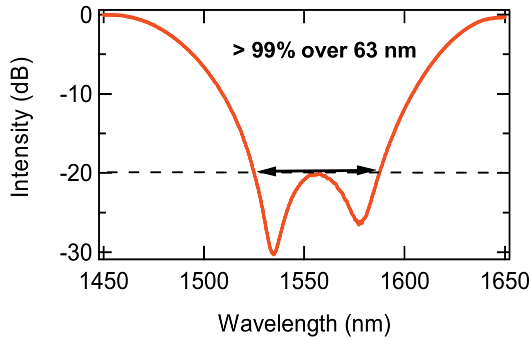
Broadband Gratings

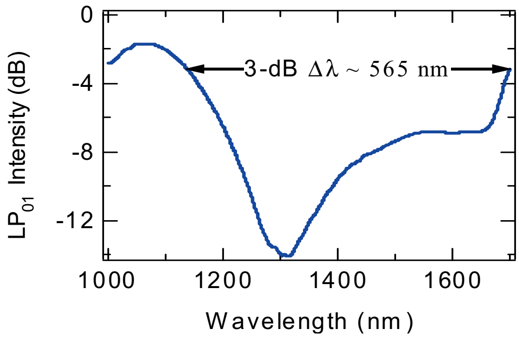


- Broadband Mode Conversion

(C.D. Poole et al, JLT, v9, p598, 1991)

(S. Ramachandran *et* al, OL, v27, p698, 2002)

$$\delta(\lambda)=\frac{1}{2}\left(\cancelto{0}{\Delta\beta(\lambda)}\cdot\Delta\lambda+\frac{\Delta\beta'(\lambda)}{2!}\cdot\Delta\lambda^2+\frac{\Delta\beta''(\lambda)}{3!}\cdot\Delta\lambda^3+\ldots\right)$$



- λ – insensitive coupling

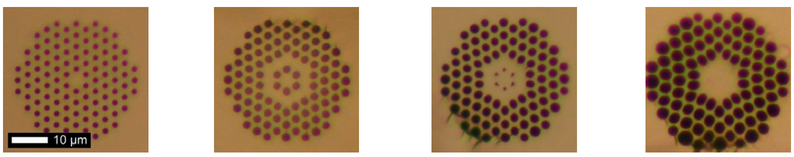
(S. Ramachandran *et* al, PTL, v15, p1561, 2003)

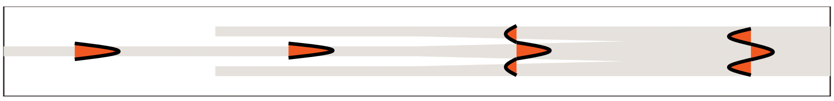
–**Match several dispersive orders**

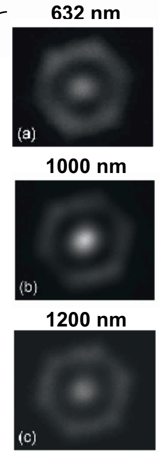
$$\delta(\lambda)=\frac{1}{2}\left(\cancelto{0}{\Delta\beta(\lambda)}\cdot\Delta\lambda+\cancelto{0}{\frac{\Delta\beta'(\lambda)}{2!}}\cdot\Delta\lambda^2+\cancelto{0}{\frac{\Delta\beta''(\lambda)}{3!}}\cdot\Delta\lambda^3+\ldots\right)$$

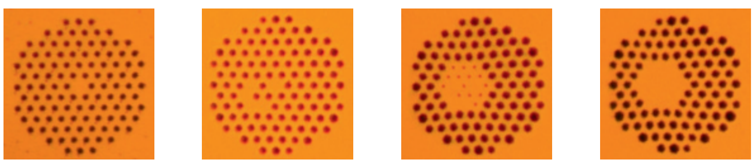
Tapered Couplers

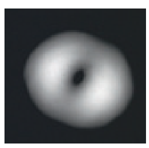
K. Lai et al, OL, v32, p328, 2007











A. Witkowska et al, OL, 33, p306, 2007

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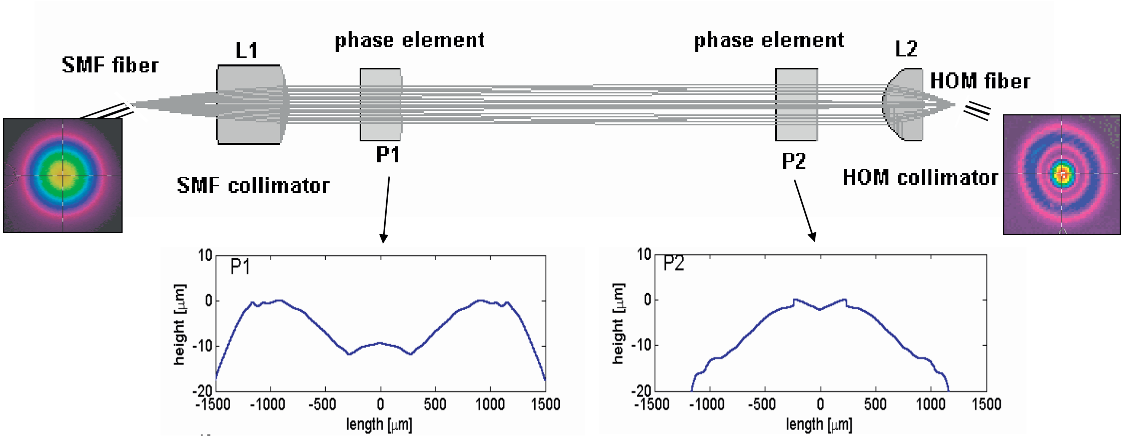
Phase Plates

One Phase Element:
need |H(x,y)| ➔ *absorptive elements* ➔ *loss*

Two Phase Elements:
free space path ➔ *convert phase variation at P1 to intensity variation at P2*



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M. Tur et al, J. Opt. Fiber. Comm. (Springer), v4, p110, 2007

Outline

- Mode Conversion
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- Dispersion control
  - High normal (-ve) dispersion… *telecom, fs pulse control*
  - Anomalous Dispersion……….. *nonlinear optics*
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  - Cylindrical vector beams, Vortices
  - Bessel beams

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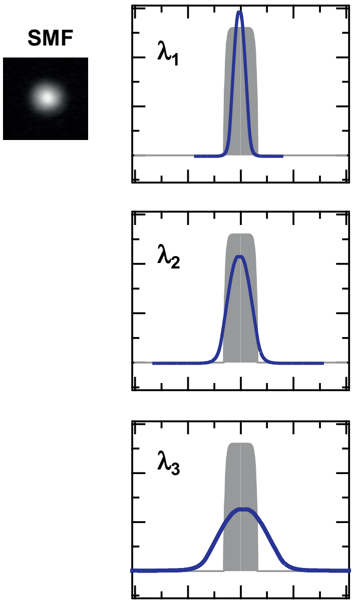
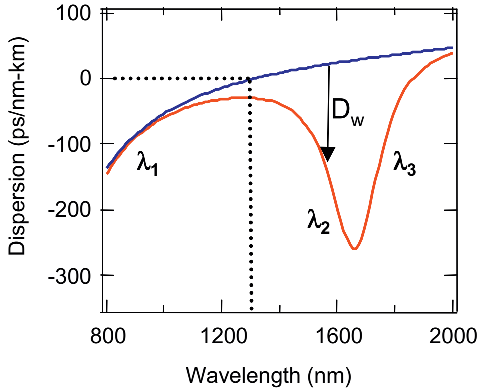
Dispersion in fibers



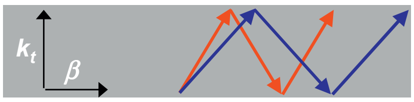
$$D = D_m + D_w; \qquad D_w = \frac{d\tau}{d\lambda}$$



Mode expands to ↓ n
⇒ $D_w < 0$
⇒ $D < D_m$

L. Gruner-Nielsen *et al*, JLT, v23, p3566, 2005

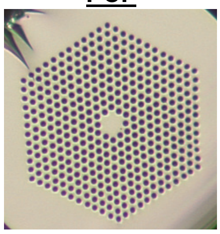
Dispersion in fibers (2)



$$\beta^2 = \left(\frac{2\pi}{\lambda}n\right)^2 - k_t^2; \qquad k_t \cdot a = m\pi$$

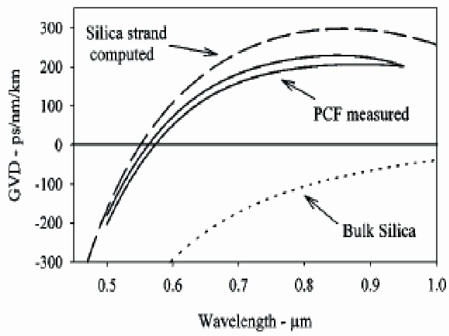
$$\lambda \uparrow \Rightarrow \tau \uparrow$$
$$\therefore D_w = \frac{d\tau}{d\lambda} > 0$$

PCF **Silica Rod**



≡ •

+D ↑ with A_{eff} ↓



L. Gruner-Nielsen *et al*, JLT, v23, p3566, 2005

J.C. Knight *et al*, PTL, v12, p807, 2000

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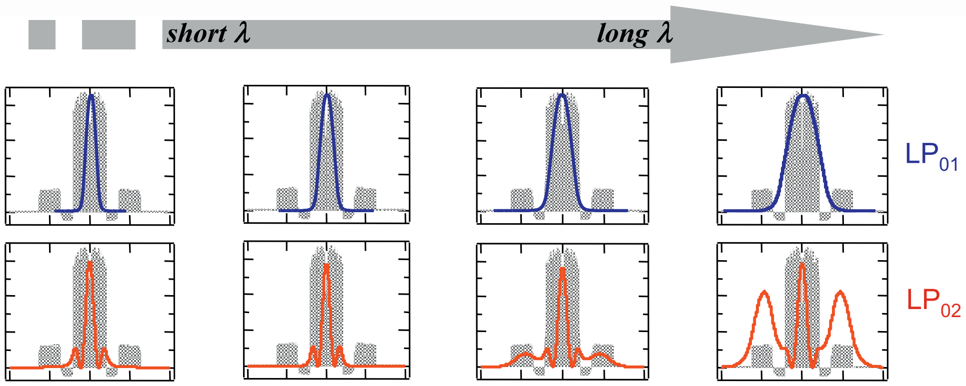
Modal evolution in fibers



• Stable mode (e.g. LP_{01})..................Mode profile expands **slowly** with λ

• Dispersive mode (e.g. LP_{02})............Side lobes expand **rapidly** with λ

Analogy to particle in a box

•Core & Ring……competing attractive wells

•Trench…………..barrier for side-lobe movement

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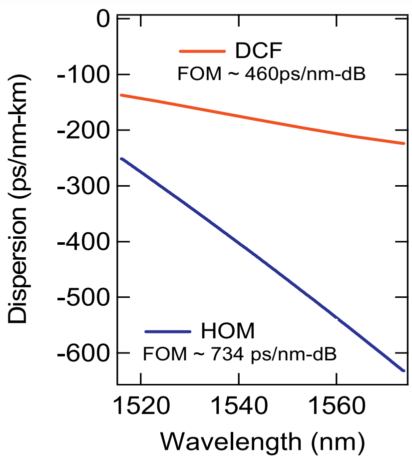
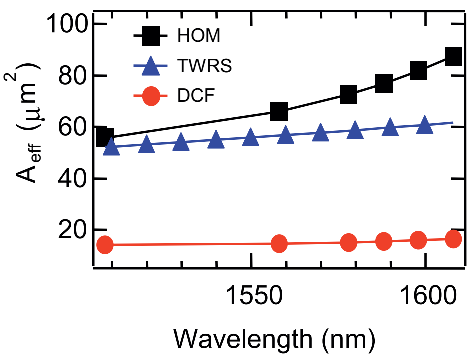
S. Ramachandran, JLT, v23, p3426, 2005

-D from HOMs





•**Higher dispersion, slope possible**

–*Lesser compensating fiber*

•**Higher FOM (d/α)**

–*Lower loss modules*

• **A_{eff} ~ 3x to 5x larger than DCF**

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S. Ramachandran et al, J. Opt. Fiber. Comm. (Springer), v3, p159, 2006

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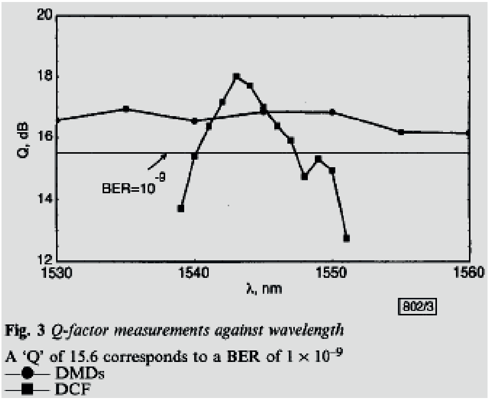
Dispersion compensation

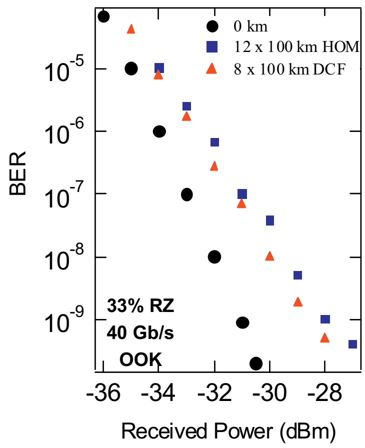
Dispersion Slope Matching



First slope-matched systems test over entire C-band with high-RDS fiber

A. Gnauck et. al, OFC-2000, PD-8

Enhanced Nonlinear Threshold



10 dBm higher input power in HOM vs. DCF

→ 50% longer transmission

S. Ramachandran et. al, ECOC-2000, PD-2.5

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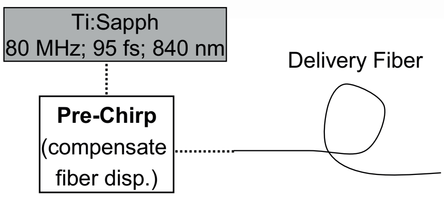
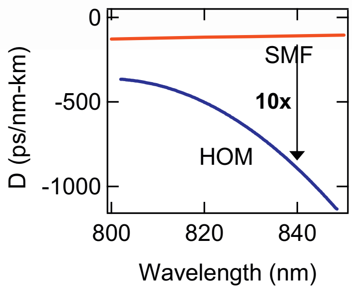
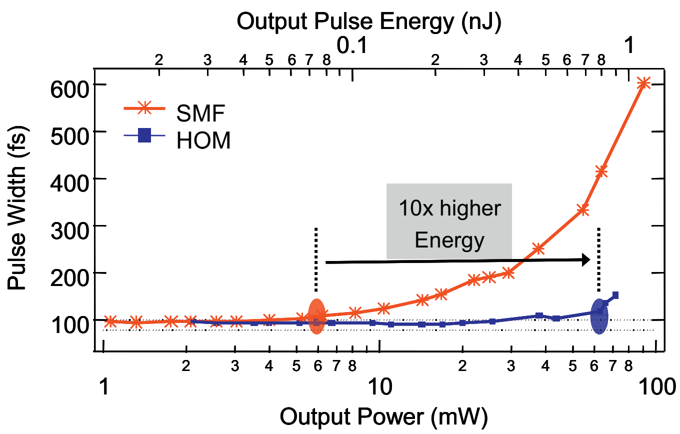
Energetic Ultra-Short Pulse Delivery



$$nonlinearity \sim \frac{1}{D \cdot A}$$





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S. Ramachandran et. al, OL, v30, p3225, 2005

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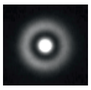
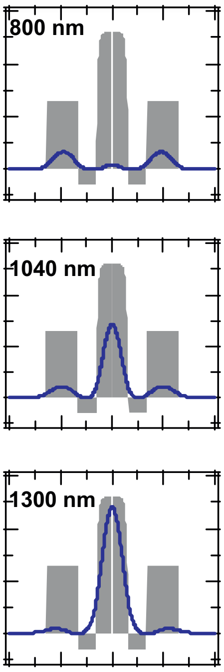
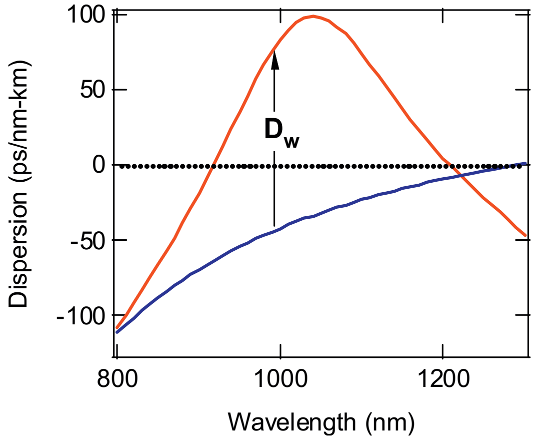
"Anomalous" mode evolution in HOMs

LP_{02}





Mode evolves in *opposite* direction => $D_w = d\tau/d\lambda > 0$



All silica fiber with ↑↑ +D
A_{eff} ~ 10 to 100x higher than PCF

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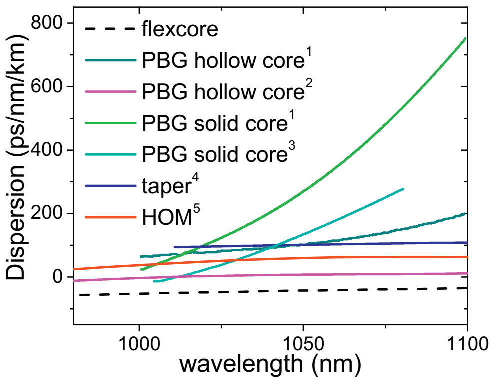
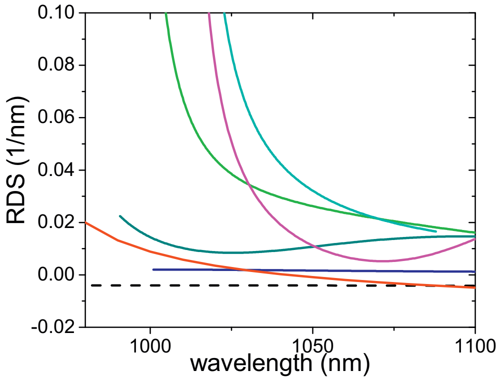
S. Ramachandran et. al, OL, v31, p2532, 2006

Dispersion control at 1 µm





+D HOMs in fs modelocked laser cavities

- **88 fs output *all fiber*** (nonlinear pol. evolution)
  – M. Shultz et al, CLEO-Europe 2009
- **52 fs output** (nonlinear pol. evolution)
  – M. Shultz et al, OL-2007
- **137 fs output *all fiber*** (carbon nanotubes)
  – J.W. Nicholson et al, Opt. Exp.-2007

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1 C.K. Nielsen et al. Opt. Exp. 14, pp 6063 (2006)
2 H. Lim et. al. Opt. Exp 12, pp 2231 (2004)
3 A. Isomaki et. al. Opt. Exp 14, pp 4368 (2006)
4 M. Rusu et. al. Opt. Lett. 31, pp 2257 (2006)
5 S. Ramachandran et. al. Opt. Lett. 31 pp 2532 (2006)

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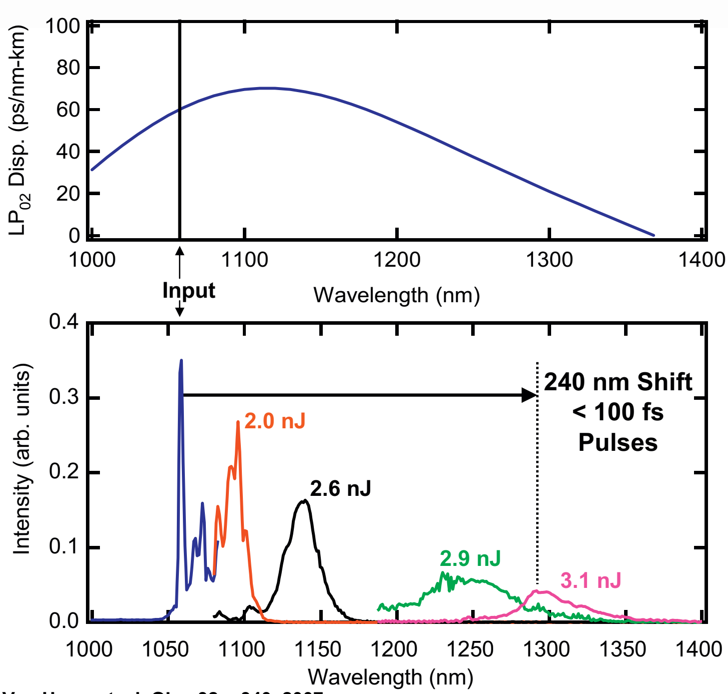
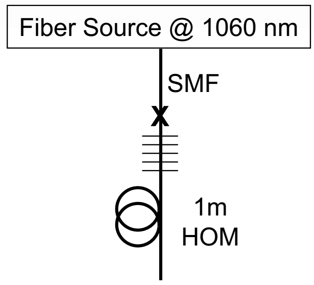
Raman-Shifted Solitons ➔ fs tunable source

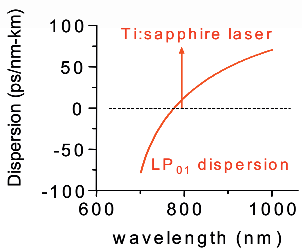




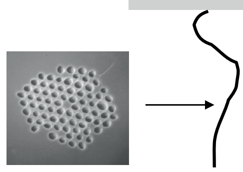
- Range ~ Ti:S + OPO
- Scale Energy by ↑ A_{eff}

J. Van Howe et. al, OL, v32, p340, 2007
J.H. Lee et. al, OFC-2007, Post-deadline

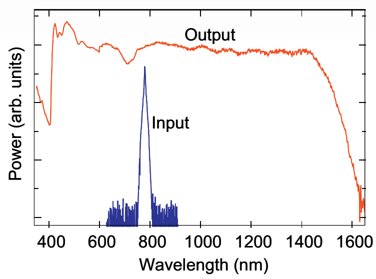
Supercontinuum Generation



High Power fs laser



J.K. Ranka *et.* al, OL., v25, p25 , 2000



Center Launch

Offset Launch

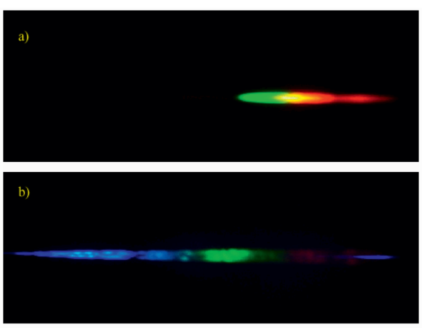
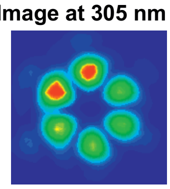


Image at 305 nm



- Anomalous dispersion in HOM
  - enhanced nonlinearities
  - new mode-conversion technique?

A. Efimov et al, Opt. Exp., v11, p910 , 2003

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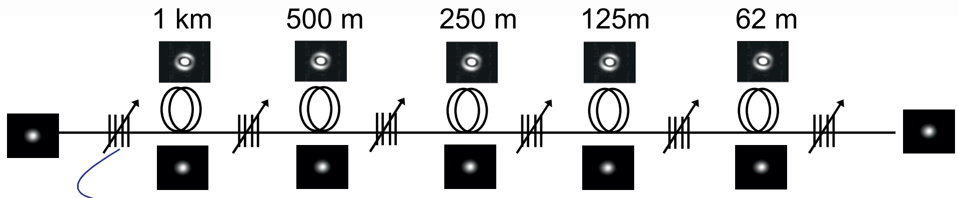
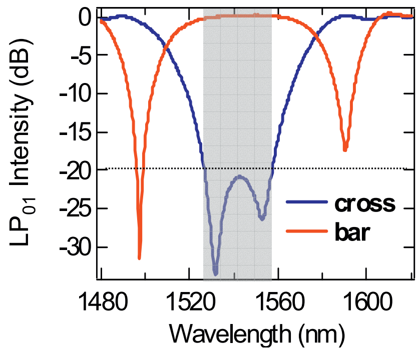
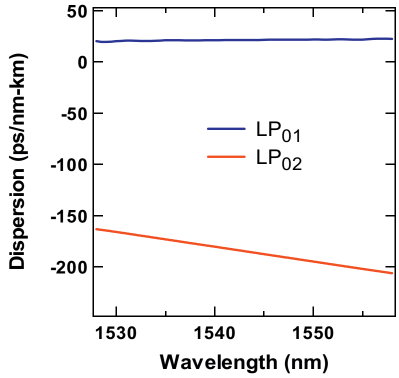
Optical Path Diversity



2 paths ➔ Number of states = 2^N = 32





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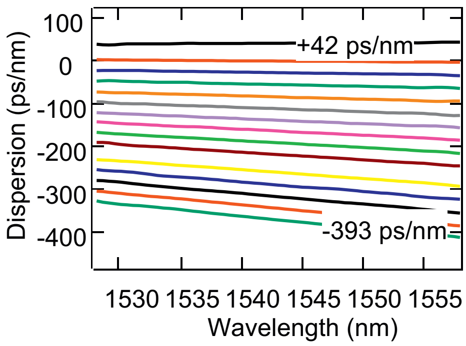
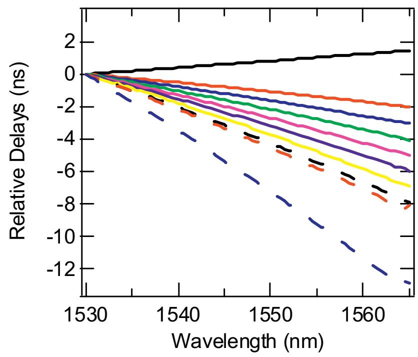
Adjustable Delay/Dispersion

Dispersion



Delay



Design Flexibility

- Slope......................HOM fiber design
- Range & Step size…..Segment lengths
- Bandwidth……………Grating design

S. Ramachandran et. al, PTL, v15, p727, 2003

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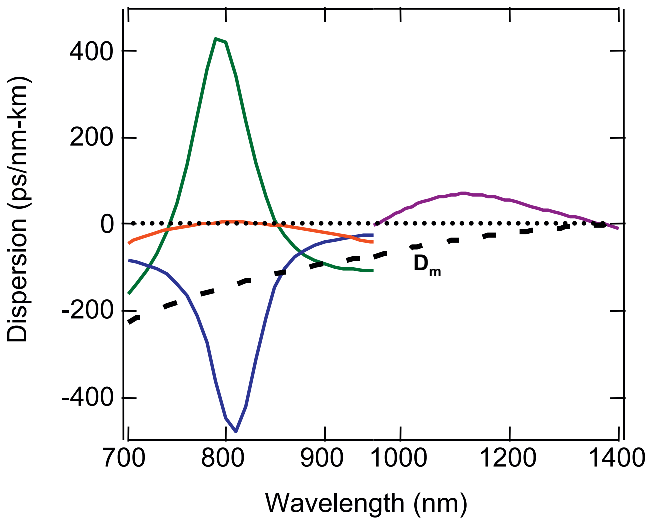
Dispersive design flexibility with other modes



Control
- D, D_{slope}, λ, D_0
  - *with range of A_{eff}*
- Low Loss (~0.1 – 0.5 dB)

Applications
- Tune λ range of source
- Disp. management of lasers
- High(er) energy ν-conversion

23

S. Ramachandran et al, J. Opt. Fiber. Comm. (Springer), v3, p159, 2006

Outline

- Mode Conversion
  - The higher-order-mode schematic
  - How to access them –*gratings, tapered couplers, holograms*
- Dispersion control
  - High normal (-ve) dispersion… *telecom, fs pulse control*
  - Anomalous Dispersion……….. *nonlinear optics*
  - Multiple paths…………………. *adjustable delays*
- Mode area control
  - Anomalous stability criteria ⇔ large mode areas
  - Applications to high-power lasers
- Free space implications
  - Beam forming
  - Cylindrical vector beams, Vortices
  - Bessel beams

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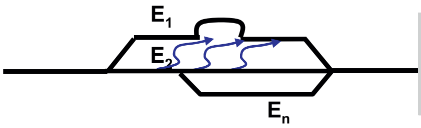
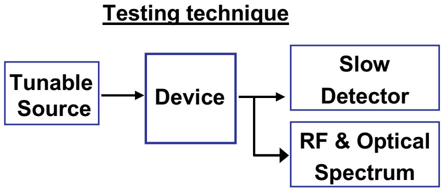
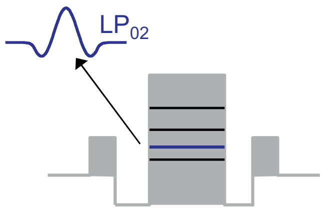
Multi-Path Interference (MPI) or Modal Noise



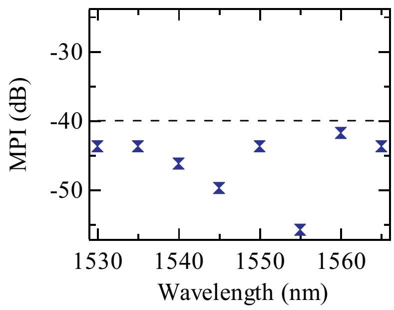
$$MPI = \left| \frac{E_{parasitic}}{E_{main}} \right|^2$$





Maximise $n_{desired} - n_{parasitic}$

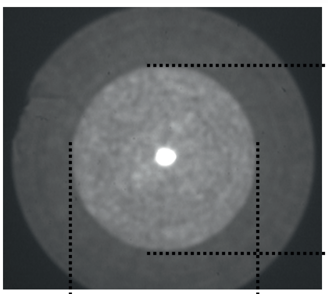
➔ minimise coupling

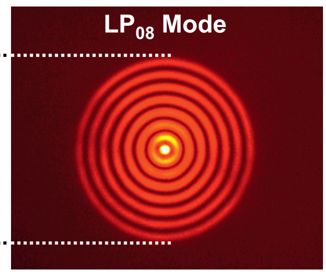


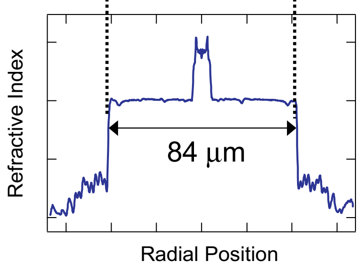
M.G. Taylor et al, ECOC-2003, 3.1.7

S. Ramachandran et. al, PTL, v15, p1171, 2003

Large A_{eff} modes







- A_{eff} ~ 1750 μm^2
- ***After 50 meters!***

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S. Ramachandran et al, OL, v31, p1797 , 2006

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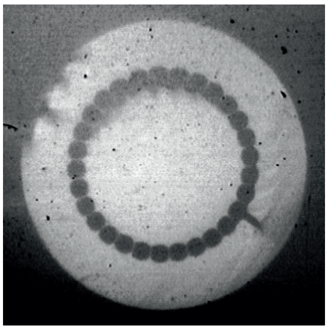
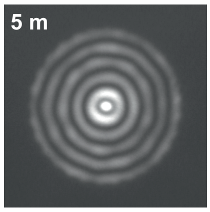
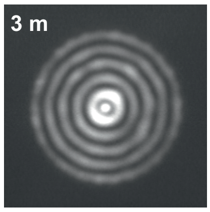
Air-clad version

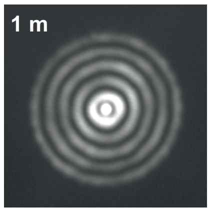
A_{eff} ~ 2400 μm^2
Air Clad defines HOM waveguide



LP_{06}: 5-cm bends







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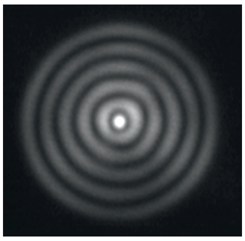
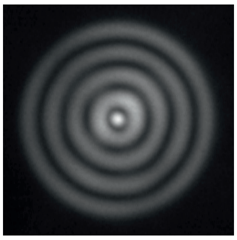
S. Ramachandran et al, J. Laser & Photonics Rev. , Dec. 2008

Other modes (1550 nm)

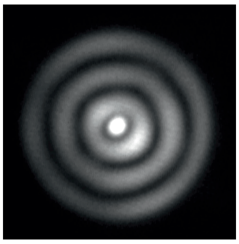
LP_{06}: 2 m; 7-cm bends



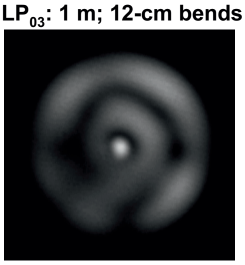
LP_{05}: 2 m; 7-cm bends



LP_{04}: 4 m; 7-cm bends



LP_{03}: 1 m; 12-cm bends



For higher mode orders:
- Stability ↑
- Bend Distortion ↓

Why?
Deeper Wells
⇒more states
⇒more coupling

J.M. Fini & S. Ramachandran, OL, v32, p748, 2007

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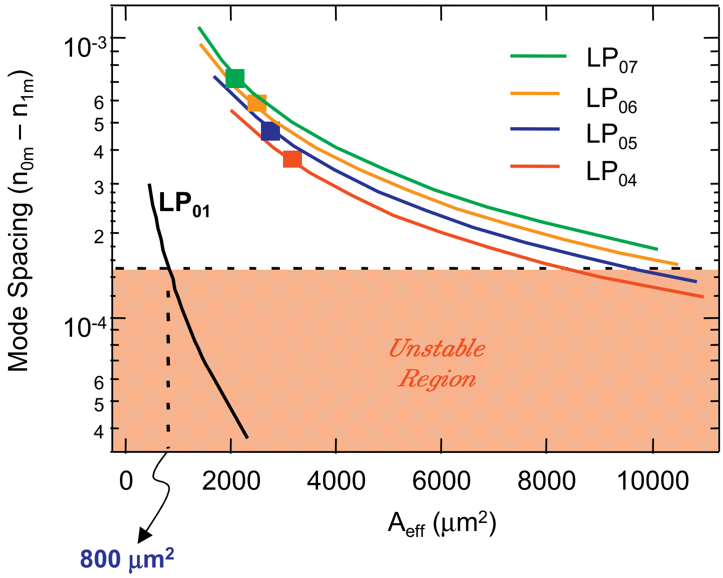
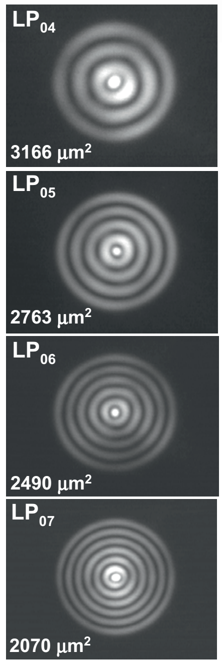
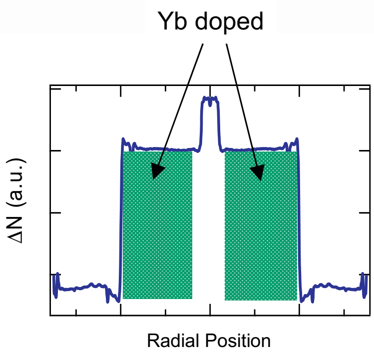
LMA *flexible* Fibers

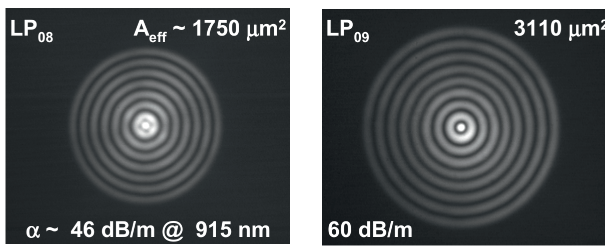


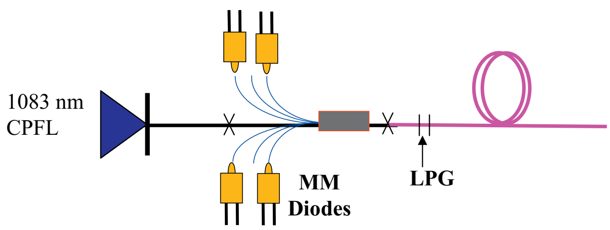


S. Ramachandran et al, J. Laser & Photonics Rev. , Dec. 2008
S. Ramachandran et al, OL, v31, p1797 , 2006
S. Ramachandran et al, Laser Focus World, Sept. 2007
S. Ramachandran et al, Photonics Spectra, Sept. 2006

Cladding Pumped Amplifiers







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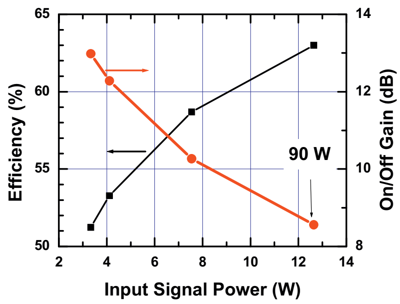
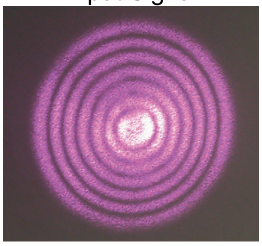
HOMs for Power Amplification

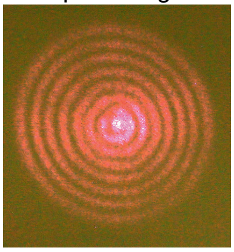
1750 μm² LP₀₈ mode



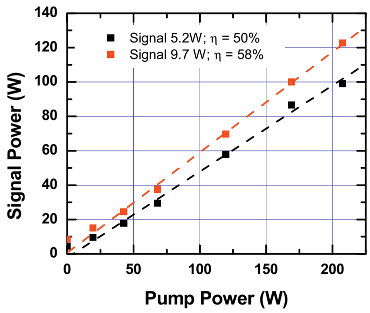
Input Signal

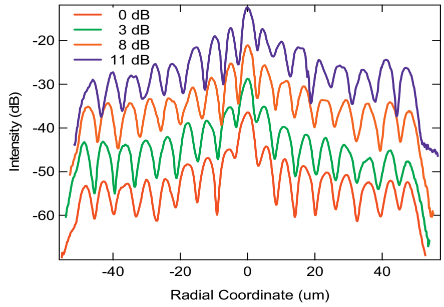


Amplified Signal



3110 μm² LP₀₉ mode





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Single-mode fiber laser based on core-cladding mode conversion

Shigeru Suzuki,* Axel Schülzgen, and N. Peyghambarian
College of Optical Sciences, University of Arizona, Tucson, Arizona 85721, USA

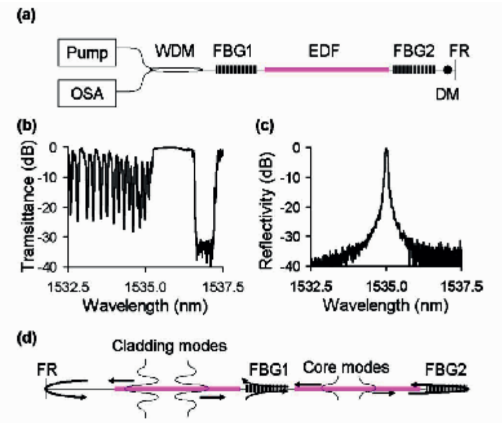

Fig. 1. (Color online) (a) Schematic of the fiber laser setup, (b) transmittance spectrum of FBG1, (c) reflectivity spectrum of FBG2, and (d) schematic of an unfolded cavity that is equivalent to the fabricated folded cavity with core-cladding mode conversion.

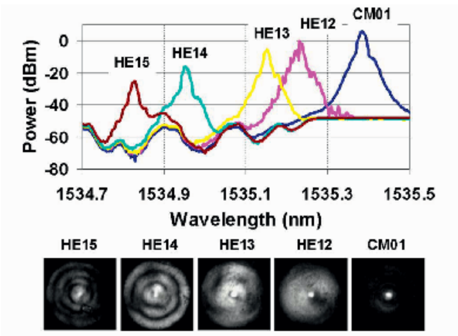

Fig. 3. (Color online) Lasing spectra and spatial profiles of the fiber laser at different temperatures of FBG2.

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S. Suzuki et al, OL, v33, p351, 2008

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Phase locking and coherent combining of high-order-mode fiber lasers

Vardit Eckhouse,* Moti Fridman, Nir Davidson, and Asher A. Friesem
Department of Physics of Complex System, Weizmann Institute of Science, Rehovot 76100, Israel

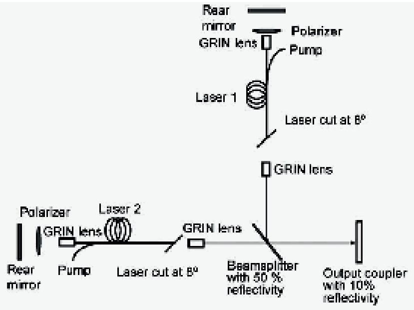

Fig. 5. Configuration for coherent addition of two fiber lasers each operating with a high-order mode.

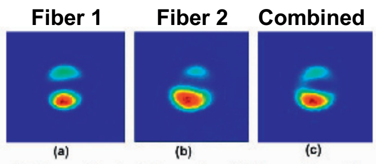

Fig. 6. (Color online) Coherent addition of two fiber lasers each operating with LP_{11} mode. (a) Intensity distribution of one laser, (b) intensity distribution from the other laser, (c) intensity distribution of the combined output.

Spatial distribution and polarisation of one laser imposed on the other

➔ feasible to lock in *any* mode?

V. Eckhouse et al, OL, v33, p2134, 2008

Outline

- Mode Conversion
  - The higher-order-mode schematic
  - How to access them –*gratings, tapered couplers, holograms*
- Dispersion control
  - High normal (-ve) dispersion… *telecom, fs pulse control*
  - Anomalous Dispersion……….. *nonlinear optics*
  - Multiple paths…………………. *adjustable delays*
- Mode area control
  - Anomalous stability criteria ⇔ large mode areas
  - Applications to high-power lasers
- Free space implications
  - Beam forming
  - Cylindrical vector beams, Vortices
  - Bessel beams

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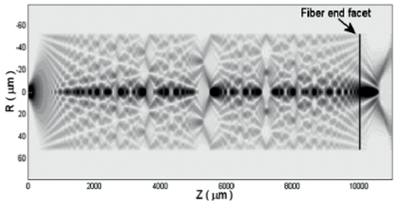
Multimode Beam Forming

Re-imaging in Multimode fibers
(W.S. Mohammed et al, JLT, v22, p469, 2004)



Fiber lens: couple multiple modes to LP_{01}
(G. Nemova et al, Opt. Comm., v261, p249, 2006)

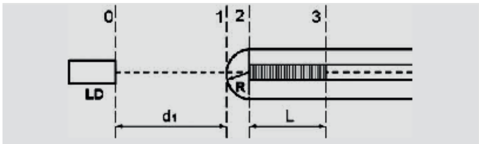


Fig. 1. Schematic diagram of the proposed coupling scheme with the hemispherical lens.

Sequential or Superimposed LPG
(M. Sumetsky et al, Opt. Exp., v16, p402, 2008)

- **Sharp beam edge, longitudinally**
- **Flat transverse beams**

X. Gu et al, PTL, v20, p1130, 2008

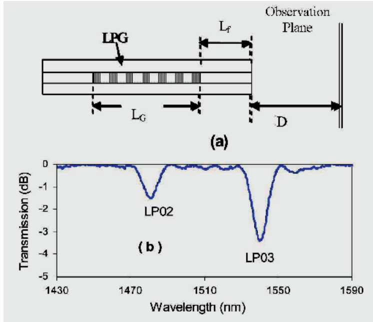


Fig. 1. (a) The schematic of the beam shaping device and (b) transmission spectrum of the LP_{03} and LP_{02} cladding modes of LPG.

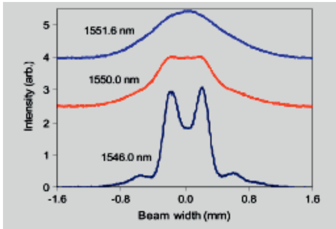
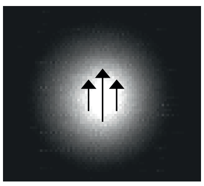
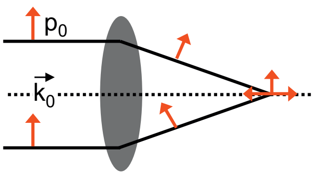


Fig. 4. The beam intensity profiles measured at 12 mm from the fiber facet at three different wavelengths. The Gaussian and top-hat beam profiles are displaced to improve visibility.

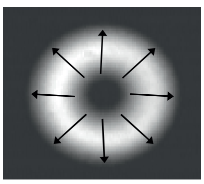
Cylindrical Vector Beams

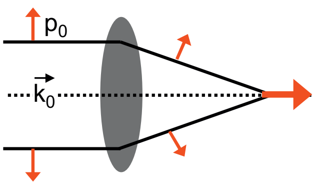
Gaussian





Radially Polarised





Radially polarised beam

- Intense E_Z with ↑↑ gradient, No S_Z!
  - resembles atomic states
    (Novotny et al, PRL **86**, 5251, 2001)
    - Quantum information
    - Probe atomic states
  - electron acceleration
    (Salamin, Phys. Rev. A **73**, 43402, 2005)
    - Free-electron lasers
  - super-resolved spots
    (Dorn et al, PRL, **91**, 233901, 2003)
    - Microscopy, Lithography
  - efficient tweezers
    (Q. Zhan, *Opt. Exp.* **12**, 3377, 2004)
- Machining of metals
  - 2x more efficient
    (Nesterov et al, *Phys. D* **33**, 1817, 2000)

Not easy to generate

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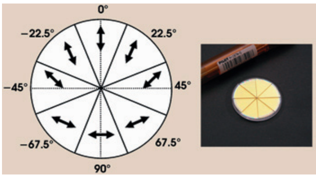
Generation of non-uniform polarisation patterns

- **Segmented waveplates**
  - restricted λs
  - low efficiency, high loss



Machavariani et al, OL 32, 1468, 2007

- **Resonator modes**
  - unstable
  - Limited λ

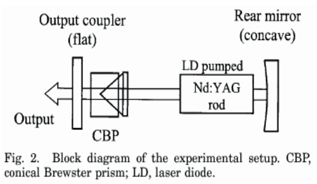
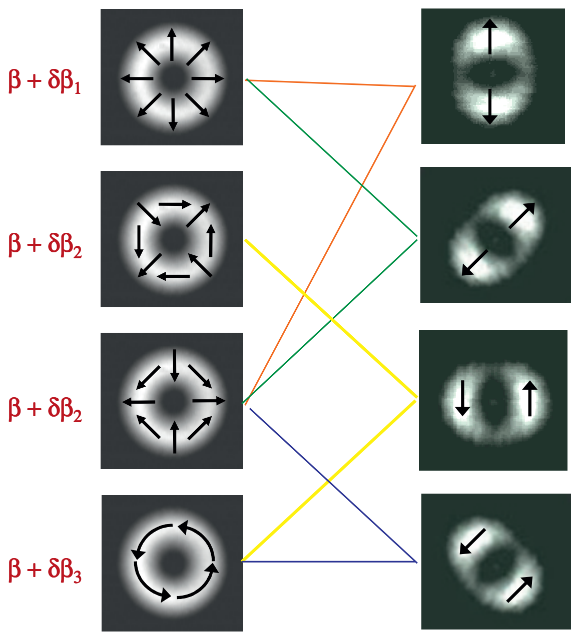
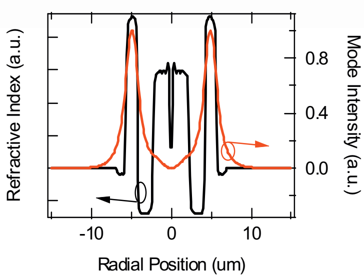


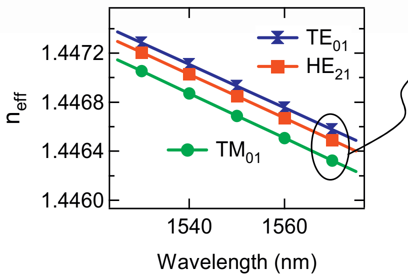
Fig. 2. Block diagram of the experimental setup. CBP, conical Brewster prism; LD, laser diode.

Y. Kozawa et al, OL 30, 3063, 2005
J-L. Li et al, OL 31, 2969, 2006

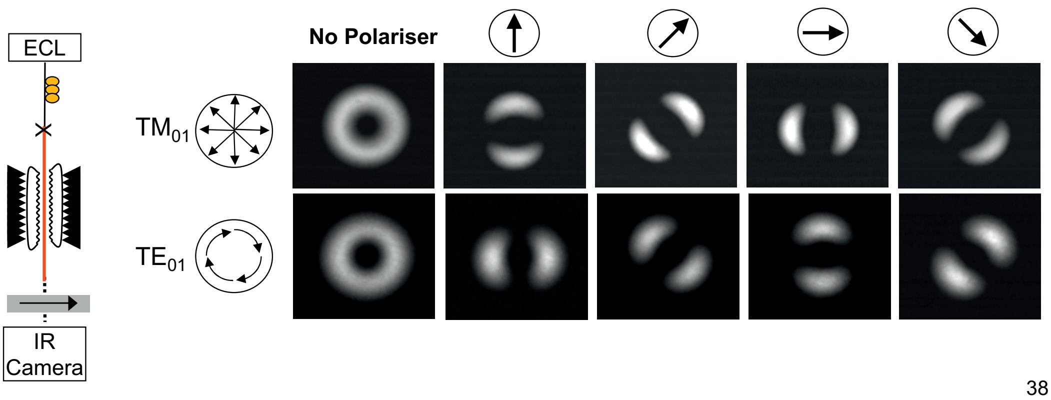


Phase Engineered Fiber





$\Delta n \sim 10^{-4}$
(~ PM fibers)



S. Ramachandran et al, OL, v34, 2009

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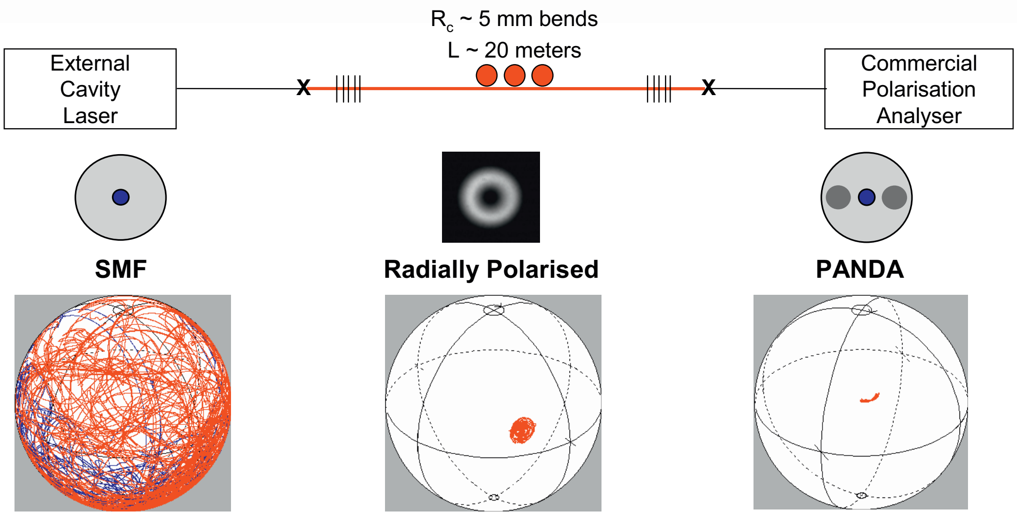
Polarisation Preservation



PER = 0 dB PER = 29 dB PER = 35 dB

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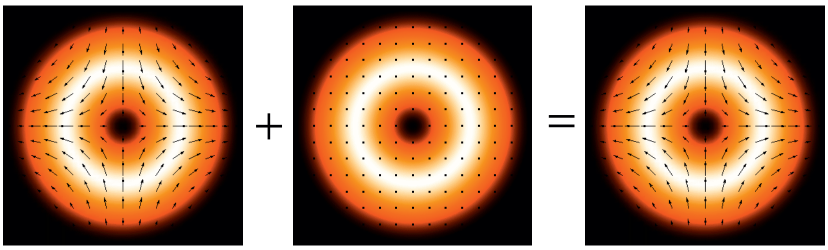
S. Ramachandran and M.F. Yan, CLEO-2008, CThV2

Helical Gratings

C.D. Poole et al, JLT, v9, p598, 1991

P. Z. Dashti et al, PRL, v 96, 043604, 2006



Output is a Vortex Beam (Spiral Phase)

$$HE_{21}^{e} + \left(-iHE_{21}^{o}\right) = HE_{21}^{e} - iHE_{21}^{o}$$

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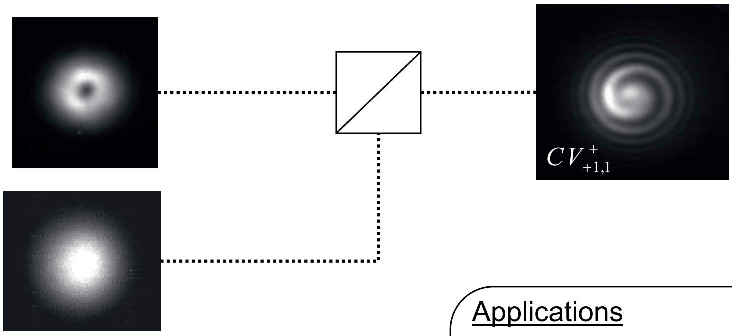
Vortex Beams

P. Z. Dashti et al, PRL, v 96, 043604, 2006



Carries Orbital Angular Momentum

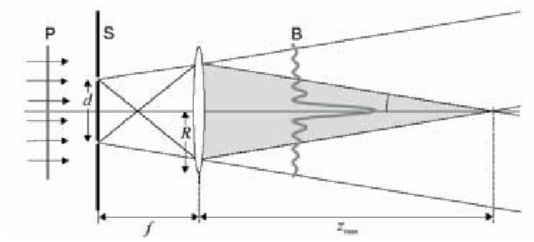
Applications

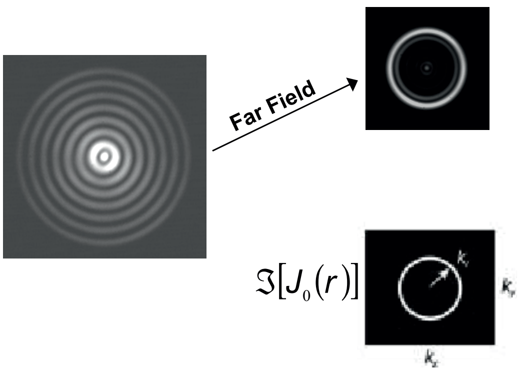
“Optical Angular Momentum,” Ed. Allen, Barnett & Padgett, Taylor & Francis (2003)

- Torque on microscopic objects
- Quantum Cryptography key distribution
- Atom optics
- Nonlinear optics with chiral symmetry

Bessel Beams

Thin Ring





Conical Plane Waves

- Diffraction free!
- Navigate past opaque obstructions

Applications

- Large depth of focus
  - –Enhanced nonlinear interactions
  - –Atom guides
- Transmit in turbid media
  - –Simultaneous cell manipulation
  - –LIDAR & space communications

Durnin et. al, PRL, v58, p1499, 1987
Dholakia et al, Contemporary Phys., v46, p15, 2005

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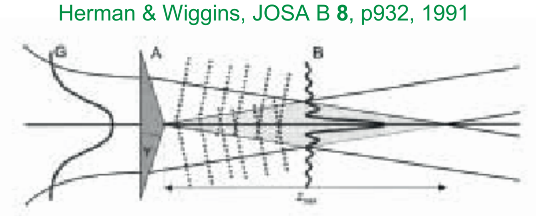
Generation Techniques

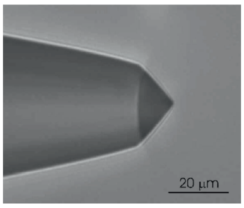
Axicons

Herman & Wiggins, JOSA B **8**, p932, 1991



Fiber microaxicon

T. Grosjean, Appl. Opt. **46**, p8061, 2007



Limited aperture => Limited diffraction-resistance

Not efficient for higher order Bessel Beams

Other free-space techniques

- Holograms
  - T. Turunen et al, Appl. Opt. **27**, p3959, 1988
- Mode selection in laser resonator
  - K. Uehara et al, Appl. Phys. B **48**, p125, 1989
- Spatial light modulators
  - N.Chattrapiban et al, Opt. Lett. **28**, p2183, 2003
- Whispering gallery mode resonators
  - V.S. Ilchenko et al, Opt. Exp. **15**, p5866, 2007

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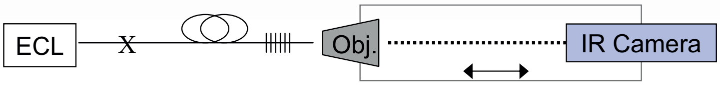
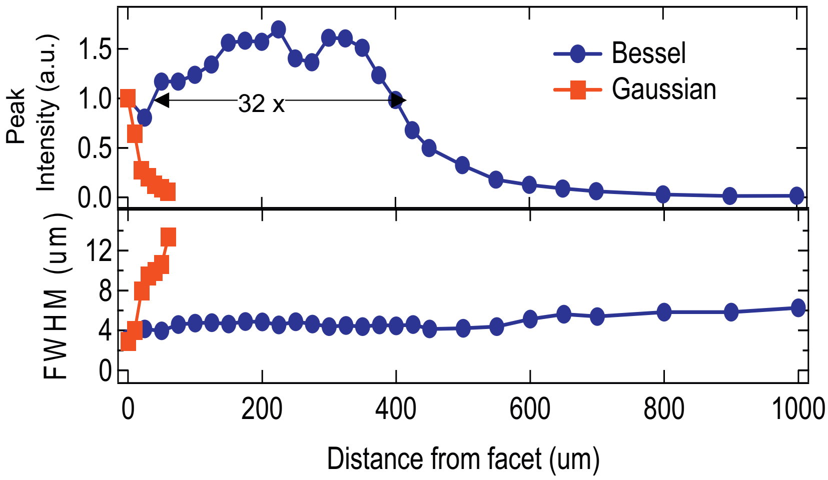
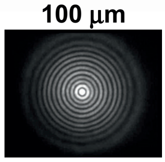
Diffraction resistant behaviour



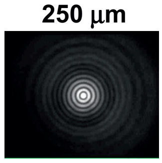


~3 µm Central Spot

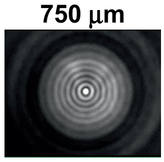
100 µm



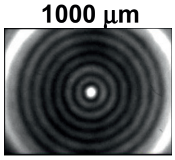
250 µm



750 µm



1000 µm



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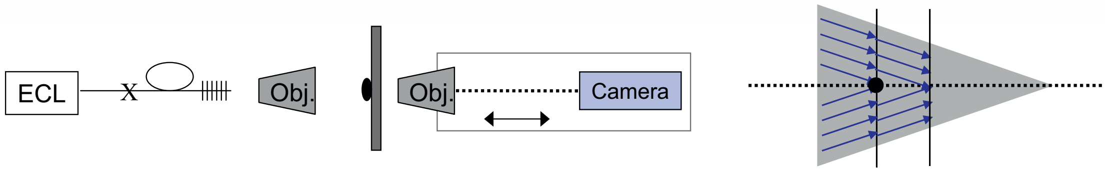
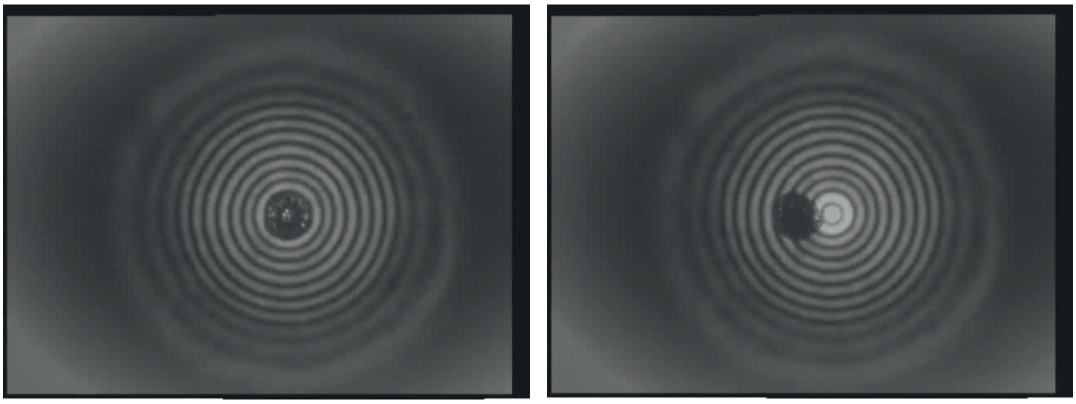
Self-healing behaviour





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S. Ramachandran and S. Ghalmi, CLEO-2008, Postdeadline, CPDB5

Spatially Structured Light offers new possibilities…

- **Unprecedented control of optical parameters…**
  - –interaction between light-paths with gratings
  - –record *D* and A_{eff} control
- **…enabling new classes of devices**
  - –ultra-high power lasers
  - –novel colour sources
  - –nonlinear switches and devices
- **Light–matter interactions*… spatial & polarisation control with a fiber***
  - –fundamental sciences… quantum state tailoring; electron acceleration
  - –biology.......................... endoscopic imaging; cell manipulation
  - –technology……………… lithography; machining; telecom

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